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Design of Robust Controllers for Automotive Applications

Ph. D. Work plan

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Design of Robust Controllers for Automotive Applications

1) A brief resume of proposed problem

In recent years, automotive industries and many researchers are showing their interest in developing intelligent controls for automobiles. Some of the areas which are being vigorously researched are the suspension systems, anti-lock braking system and active steering to mention only a few. Out of many one of the major challenging areas for the researchers and automotive industrialists is to develop suspension system to give ride comfort to the passengers. Suspension system in an automobile isolates the vehicle body (hereafter referred as sprung mass) from the rough road to provide better ride comfort while meeting the constraints of rattle space and maintaining a firm contact with the road i.e. also called as road holding property.

Ride comfort is the measure of vertical acceleration of the sprung mass. The fact that the rattle space i.e. the space between tire (hereafter referred as unsprung mass) and the sprung mass, is limited putting a constraint on the achievable ride comfort. If the suspension deflection crosses the rattle space limit, it causes great discomfort to the passengers and can also damage the suspension components too. They dynamic tire force that are developed during a journey have a direct impact on the road holding and in turn on the ride safety. It is desirable to simultaneously keep the sprung mass acceleration, the suspension deflection and the dynamic tire force small but practically, these three desirable attributes conflict with each other. Further difficulties while designing suspension system are uncertain and nonlinear behavior of the suspension components, unknown road profiles and uncertain passenger loading. Designing a single suspension system which meets all the desired attributes simultaneously is really a very difficult task.

A conventional suspension system is a passive system comprising of springs and dampers only. The damping coefficient and the spring stiffness of a passive suspension system are fixed because of which the performance of the passive suspension is limited. Secondly suspension system is affected by the inherent nonlinear behavior of springs and dampers and disturbances. In a semiactive suspension system, performance is improved by changing the damping coefficient in real time. In an active suspension system, an actuator is connected between the sprung mass and the unsprung mass I parallel with a spring and a damper. The actuator is capable of generating a force that changes the suspension characteristics in a variety of ways. This property of active suspension system has attracted the attention of researchers and automotive industries since a long time.

2) Introduction to proposed research topic.

Observer Based Robust Control Design: In order to control any system, we should know exact parameters of the system, disturbances acting on the system, states of that particular system etc. But, many of the times parameters of the system may not be known exactly or the parameters changes because of the change in temperature, ageing effect etc. Because of which there is always an uncertainty in the systems parameter. Disturbances acting on the system cannot be known exactly because if the disturbances acting on the system are known exactly then they will no longer be called as disturbances. Many of the times, not all the states of the system are available at the output for measurement. Even though the states are available, there might not be the availability of sensors to measure it or the sensors available for the measurement are very costly. During such situations, it is better to estimate them and then design a robust controller that can work effectively even with this uncertainties, disturbances and unavailable states.

For estimation purpose, a technique called the observer is used. There are many observers used for estimation purpose. Like disturbance observer (DO), inertial delay control (IDC), uncertainty and disturbance observer (UDE) etc. are used for estimating the uncertainties and disturbances. Luenberger observer, generalized state observer (GSO), extended state observer (ESO) etc. are used for the estimation on states of an observable system.

3) Review of literature and development in the relevant subject

The development in vehicle suspension design and control are reviewed in many survey papers [1, 2, 3, 4, 5]. The overview of advances in vehicle suspension design, dynamics and control is presented in [1]. The basic principles of active suspension design in order to get a better compromise between the ride comfort and handling is discussed in [2] and is followed by the practical considerations involved in [3]. The application of Linear Quadratic Regulator (LQR) to vehicle suspension systems is discussed in [4] and [5]. An overview of intelligent methodologies like fuzzy, neural networks, genetic algorithms and their applications to active suspension systems is taken in [6].

A control scheme known as sky-hook damping, which aims to achieve the same damping force as would be produced by a conceptual damper connected to an ideal inertial reference in the sky was proposed by Karnopp in the 1970's and is still employed by many researchers as in [7, 8, 9, 10, 11]. The sky hook damping improves the ride comfort but it cannot be physically realized. The effect of sky-hook damping can be synthetically generated by active control. Model reference adaptive control aims to make the output of the suspension to follow a desired reference model. Its application to active suspension has been proposed in [7, 8, 9, 10] among others. Since it is difficult to find an accurate model of the suspension system, many researchers have proposed solutions based on model free strategies like the fuzzy control, fuzzy control with genetic algorithms and neural network [15, 16, 17, 18].

Optimal control strategies based on LQR and Linear Quadratic Gaussian has been proposed by several workers [19, 20, 21]. In these strategies a performance index based on sprung mass acceleration, tire and suspension deflection is minimized. Linear Quadratic Optimal controls work well for linear systems that are relatively free form uncertainties and disturbances. Therefore some researchers have used adaptive control schemes which provide self-tuning feedback gains so as to fulfill the performance aspects [22, 23, 24]. A road adaptive scheme, in which the gain of the controller is adjusted according to the type of the road surface and vehicle speed is proposed in [22]. A nonlinear adaptive control is proposed in [7]. A strategy to adapt to future road profiles is suggested in [25].

Another well-known strategy for control of uncertain systems affected by unmeasurable disturbances is the Sliding Mode Control (SMC) strategy. In SMC, the control is designed in such a way that the system trajectories starting from anywhere hit a user chosen sliding surface and remain on it thereafter. Once on the sliding surface, the control constrains the trajectories to slide along the surface. The system is governed by the equations of the sliding surface. This renders the system in sliding mode to be insensitive to uncertainties and disturbances. The SMC is not model-free but can guarantee invariance for matched uncertainties and disturbances having a known bound. That application of SMC and its combinations with other strategies are reported in [8, 13, 14, 18, 26]. SMC is also designed for a nonlinear full vehicle in which dynamics of the actuator is taken into account [27].

The performance of an active suspension system can be improved if accurate information about the road profile is obtained in real time. In the literature efforts to obtain this information directly and indirectly are reported. Some researchers have tried to obtain this information directly using special sensors or by using lead vehicles as sensors. A system with preview control employing a vehicle mounted preview sensor is

proposed in [28, 29], while the use of the lead vehicle in a convoy as a preview sensor is proposed in [64]. Other results where vehicle sensors are used for preview control are seen in [30], [31]. Some researchers have obtained the information about the uncertainties and the road disturbance indirectly, obviating the need for employing special sensors by using the function approximation technique [32, 33, 34] and by designing of observers [35].

There are some general methods such as the Time Delay Control (TDC) [36], the Uncertainty and Disturbance Estimator (UDE) also called as Inertial Delay Control (IDC) [37, 38, 39] and the Disturbance Observer (DO) [21] have the potential to provide estimates of uncertainties and the road disturbance. Preliminary results exploring the potential of UDE and DO to active suspension system are seen in [41], [42].

The design of active suspension poses further challenges because the ride comfort is to be improved while coping up with the limitations of the rattle space and the requirement of minting good road holding at all time [11, 12]. One or more of these issues are addressed in the literature using a variety of control techniques like the adaptive Backstepping, optimal control, adaptive robust control, extended state observer.

Actuator lags, saturation and changes in inertial properties are some other issues concerned with active suspension [43]. In [44, 45] an active suspension system to compensate for actuator lag is proposed. An adaptive robust control is proposed in [46] for suspension systems that encounter actuator saturation during operation. Some recent research deals with active suspension with other objectives like the roll over prevention [47], antilock braking [48] and fault tolerance [49].

4) Objectives of the research and proposed hypothesis.

1. Study of various Disturbance estimation and compensation techniques.
2. To improve the ride comfort of the passengers and to keep the suspension deflection within the rattle space limit.
3. To develop new control strategies for active suspension systems for vehicles so that the ride comfort is improved by compensating the effect of uncertainties of the suspension system and the unknown road profile.
4. To propose new ways to handle the conflict between ride comfort and the rattle space limit.

5) Methodology to be used and adopted

The following methodology is used to meet the objective and according the work is divided into distinct phases:

- Study of uncertainty and disturbance estimation methods like the IDC, DO, GSO etc. so as to use them for estimating uncertainties, disturbances and unavailable states.
- Study of various robust control designing methods like sliding mode control, H infinity, MPC etc.
- Effects of uncertainties and disturbances will be estimated and nullified by using the opposite of the estimates in the designed control laws.
- Use of sliding mode control in combination with different observers to fulfill the objective.
- Control schemes will be validated by simulation in MATLAB/ Simulink environment as well as by conducting experiments on a laboratory setup.
- Evaluating the performance in several ways including the guidelines given in ISO standards.

6) Importance of the study

Importance of the study of vehicle dynamics and designing a observer based robust control strategies for it can be understood form the following research problems.

- **Providing Ride comfort under Uncertainties and Disturbances.** The major source of uncertainties and disturbances are
    - Uncertainties in suspension components
    - Uncertain passenger loading
    - Unknown road profile.

  The values of the spring and damper coefficients are at best known inaccurately. Further, the Coefficients change over a period of time due to wear and tear. The spring and damper models are nonlinear as well.

  The sprung mass varies according to passenger loading and directly affects the ride comfort. Getting an accurate estimate of the sprung mass is difficult.

  A rough road is a main cause of passenger discomfort. Since road profiles are unknown and difficult to predict, compensating their effect is a major challenge in assuring goof ride comfort.
- **Handling conflict between Ride Comfort and Adherence to Rattle Space Limit.**

  A good suspension system is required to assure good ride comfort and adhere to the rattle space limit at all the time. Ride comfort is obtained if magnitude of the acceleration of the sprung mass is kept small but this in turn requires a large suspension deflection if the road disturbance is large. This gives rise to the possibility of the suspension deflection hitting the rattle space limit which can result in great discomfort to passengers and possible damage to the suspension components. Therefore there is an inherent conflict between the ride comfort and the adherence to the rattle space limit. It is not possible to keep both the sprung mass acceleration and the suspension deflection small at the same time.

7) Proposed work plan- with a tentative chapter scheme

- Chapter 1: Introduction and Literature Survey
- Chapter 2: Improvement of ride comfort using observer based robust control
- Chapter 3: Improvement of ride comfort using another type of observer based robust control
- Chapter 4: Dual objective active suspension using observer based robust control design
- Chapter 5: Dual objective semiactive suspension using a nonlinear control law
- Chapter 6: Integration of active suspension system to antilock braking system and steering system for roll control during cornering.
- Chapter 7: Comparative study and stability analysis
- Chapter 8: Conclusion

8) Year wise plan of work and targets to be achieved

Sr. No.	Year 1	Year 2	Year 3
1	Detailed study of automotive dynamic systems for quarter car, half car and full car models along with detailed mathematical modelling	Study of different nonlinearities present in the actuator of active suspension system.	Study and Investigation of various observer based robust control laws so as to apply them to the integrated system of suspension, antilock braking system and steering.
2	Study and Design of observer based robust control law.	Design and Investigation of observer based control strategies so as to deal with nonlinearities present in the actuator.	Comparative study, stability analysis, accuracy, robustness and efficacy of proposed control strategies.
3	Implementation of the strategies given in the literature using MATLAB, Simulink and Car Sim software.	Experimentation and real time implementation of observer based control strategies.	Preparation of Thesis Report

9) Expected outcome

1. Design/improvement of some new or existing observers so as to improve the dynamics of automobile.
2. Reduction in the number of sensors required for the measurement of states.
3. Since the number of sensors to be used for the measurement of states will be reduced, cost of automobile will definitely be minimized.

10) References

1 D. Cao, X. Song, and M. Ahmadian, "Editor's perspectives: road vehicle suspension design, dynamics and control," *Vehicle System Dynamics*, vol. 49, no. 1-2, pp. 3–28, Jan.-Feb. 2011.

2 R. A. Williams, "Automotive active suspensions part 1: basic principles," *Proc. IMechE Part D: J. Automobile Engineering*, vol. 211, pp. 415–426,1997.

3 "Automotive active suspensions part 2: practical considerations," *Proc. IMechE Part D: J. Automobile Engineering*, vol. 211, pp. 427–444, 1997.

4 "Survey of advanced suspension developments and related optimal control applications," *Automatica*, vol. 33, no. 10, pp. 1781–1817, 1997.

5 H. E. Tseng and D. Hrovat, "State of the art survey: active and semi-active suspension control," *Vehicle System Dynamics*, vol. 53, no. 7, pp. 1034–1062, Jul. 2015.

6 J. Cao, H. Liu, P. Li, and D. J. Brown, "State of the art in vehicle active suspension adaptive control systems based on intelligent methodologies," *IEEE Trans. Intell. Transp. Syst.*, vol. 9, no. 3, pp. 392–405, Sep. 2008.

7 M. Sunwoo, K. C. Cheok, and N. Huang, "Model reference adaptive control for vehicle active suspension systems," *IEEE Trans. Ind. Electron.*, vol. 38, no. 3, pp. 217–222, Jun. 1991.

8 B. Mohan and S. B. Phadke, "Variable structure active suspension system," in *Intl Conf IEEE IECON*, 1996, pp. 1945–1948.

9 V. S. Deshpande and S. B. Phadke, "Sliding mode control of active suspension systems using an uncertainty and disturbance estimator," in *the Proceedings of Second International Conference on Control, Communication and Power Engineering, CCPE 2011*, V. Das and N. Thankachan, Eds., ACEEE- a division of IDEX. Pune, India: Springer LNCS-CCIS, 2011, pp. 15–20.

10 C. Kim and P. I. Ro, "A sliding mode controller for vehicle active suspension systems with non-linearities," *Proc. IMechE Part D: J. Automobile Engineering*, vol. 212, pp. 79–92, 1998.

11 S. B. A. Kashem, M. Ektesabi, and R. Nagarajah, "Comparison between different sets of suspension parameters and introduction of new modified skyhook control strategy incorporating varying road condition," *Vehicle System Dynamics*, vol. 50, no. 7, pp. 1173–1190, Jul. 2012.

12 M. Sunwoo, K. C. Cheok, and N. Huang, "Model reference adaptive control for vehicle active suspension systems," *IEEE Trans. Ind. Electron.*, vol. 38, no. 3, pp. 217–222, Jun. 1991.

13 B. Mohan, J. P. Modak, and S. B. Phadke, "Vibration control of vehicles using model reference adaptive variable structure control," *Advances in Vibration Engineering*, vol. 2, no. 4, pp. 343–361, Oct.- Dec. 2003.

14 C. Kim and P. I. Ro, "A sliding mode controller for vehicle active suspension systems with non-linearities," *Proc. IMechE Part D: J. Automobile Engineering*, vol. 212, pp. 79–92, 1998.

15 N. Al-Holou, T. Lahdhiri, D. S. Joo, J. Weaver, and F. Al-abbas, "Sliding mode neural network inference fuzzy logic control for active suspension systems," *IEEE Trans. on Fuzzy Syst.*, vol. 10, no. 2, pp. 234–246, Apr. 2002.

16 I. I. Esat, M. Saud, and S. N. Engin, "A novel method to obtain a realtime control force strategy using genetic algorithms for dynamic systems subjected to external arbitrary excitations," *J. Sound and Vibration*, pp. 27–48, Apr. 2011.

17 Y. H. Wang and M. C. Shih, "Design of genetic-algorithm-based self-tuning sliding fuzzy controller for an active suspension system," *Proc. IMechE Part I: J. Systems and Control Engineering*, vol. 225, pp. 367–383, Jun. 2011.

18 J. Lin, R.-J. Lian, C.-N. Haung, and W.-T. Sie, "Enhanced fuzzy sliding mode controller for active suspension systems," *Mechtronics*, vol. 19, pp. 1178–1190, 2009.

19 D. Hrovat, "Optimal active suspension structures for quarter-car vehicle models," *ASME J. Dyn. Syst. Meas. Control*, vol. 26, no. 5, pp. 845–860, 1990.

20 "Applications of optimal control to advanced automotive suspension design," *ASME J. Dyn. Syst. Meas. Control*, vol. 115, pp. 328–342, 1993.

21 S. Chen, R. He, H. Liu, and M. Yao, "Probe into necessity of active suspension based on LQG control," *Physics Procedia*, vol. 25, pp. 932 – 938, 2012.

22 I. Fialho and G. J. Balas, "Road adaptive active suspension design using linear parameter-varying gain-scheduling," *IEEE Trans. Control Syst. Technol.*, vol. 10, no. 1, pp. 43–54, Jan. 2002.

23 A. Alleyen and J. K. Hedrick, "Nonlinear adaptive control of active suspensions," *IEEE Trans. Control Syst. Technol.*, vol. 3, no. 1, pp. 845–860, Mar. 1995.

24 A. J. Truscott, "Composite active suspension for automotive vehicles," *Computing and Control Engineering Journal*, pp. 149–154, Jun. 1994.

25 J. Michael and M. Gerdts, "Pro-active optimal control for semi-active vehicle suspension based on sensitivity updates," *Vehicle System Dynamics*, vol. 53, no. 12, pp. 1721–1741, 2015.

26 R. J. Lian, "Enhanced adaptive self-organizing fuzzy sliding mode controller for active suspension systems," *IEEE Trans. Ind. Electron.*, vol. 60, no. 3, pp. 958–968, Mar. 2013.

27 Chamseddine, T. Raharijaona, and H. Noura, "Sliding mode control applied to active suspension using nonlinear full vehicle and actuator dynamics," in *IEEE Conf. on Dec. and Contr.*, Dec.

2006, pp. 3597–3602.
28 M. Abdel-Hady, “Active suspension with preview control,” *Vehicle System Dynamics*, pp. 1–13, 1994.
29 S. Ryu, Y. Park, and M. Suh, “Ride quality analysis of a tracked vehicle suspension with a preview control,” *Journal of Terramechanics*, vol. 48, pp. 409–417, 2011.
30 C. Gohrle, A. Schindler, A. Wagner, and O. Sawodny, “Design and vehicle implementation of preview active suspension controllers,” *IEEE Trans. Control Syst. Technol.*, vol. 22, no. 3, pp. 1135–1142, May. 2014.
31 “Road profile estimation and preview control for low-bandwidth active suspension systems,” *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 5, pp. 2299–2310, Oct. 2015.
32 P. C. Chen and A. C. Huang, “Adaptive multisurface sliding mode control of hydraulic active suspension systems based on the function approximation tecnique,” *J. Sound and Vibration*, pp. 685–706, 2005.
33 H.-Y. Chen and S.-J. Huang, “Functional approximation-based adaptive sliding control with fuzzy compensation for an active suspension system,” *Proc. IMechE Part D: J. Automobile Engineering*, vol. 219, pp. 1271–1280, 2005.
34 “Adaptive sliding mode control of non-autonomous active suspension systems with time-varying loading,” *J. Sound and Vibration*, vol. 282, pp. 1119–1135, 2005.
35 T. Yoshimura, A. Kume, M. Kurimoto, and J. Hing, “Construction of an active suspension system of a quarter car model using the concept of sliding mode control,” *J. Sound and Vibration*, vol. 239, no. 2, pp. 187–199, 2001.
36 K. Youcef-Toumi and O. Ito, “A time delay controller for systems with unknown dynamics,” *ASME J. Dyn. Syst. Meas. Control*, vol. 112, no. 1, pp. 133–142, 1990.
37 Q.-C. Zhong and D. Rees, “Control of uncertain lti systems based on an uncertainty and disturbance estimator,” *ASME J. Dyn. Syst. Meas. Control*, vol. 126, no. 4, pp. 905–910, Dec. 2004.
38 S. E. Talole and S. B. Phadke, “Model following sliding mode control based on uncertainty and disturbance estimator,” *ASME J. Dyn. Syst. Meas. Control*, vol. 130, no. 3, p. 034501, 2008.
39 “Control of uncertain nonlinear systems using an uncertainty and disturbance estimator,” *ASME J. Dyn. Syst. Meas. Control*, vol. 134, pp. 024 501–7, Mar. 2012.
40 W. H. Chen, “Nonlinear disturbance observer-enhansed dynamic inversion control of missiles,” *Journal of Guidance, Control and Dynamics*, vol. 26, no. 1, pp. 161–166, Jan.-Feb. 2003.
41 V. S. Deshpande and S. B. Phadke, “Sliding mode control of active suspension systems using an uncertainty and disturbance estimator,” in *the Proceedings of Second International Conference on Control, Communication and Power Engineering, CCPE 2011*, V. Das and N. Thankachan, Eds., ACEEE- a division of IDEX. Pune, India: Springer LNCS-CCIS, 2011, pp. 15–20.
42 V. S. Deshpande, M. Bhaskara, and S. B. Phadke, “Sliding mode control of active suspension systems using a disturbance observer,” in *the Proceedings of 12th IEEE Workshop on Variable Structure Systems, VSS’12*. Mumbai, India: IIT, Bombay, Jan. 2012, pp. 70–75.
43 “Vibration isolation for active suspensions with performance constraints and actuator saturation,” *IEEE/ASME Trans. Mechatronics*, vol. 20, no. 2, pp. 675–683, Apr. 2015.
44 N. Yagiz and Y. Hacioglu, “Backstepping control of a vehicle with active suspensions,” *Control Engineering Practice*, vol. 16, no. 12, pp. 1457–1467, 2008.
45 W. Sun, H. Pan, and H. Gao, “Filter-based adaptive vibration control for active vehicle suspensions with electro-hydraulic actuators,” *IEEE Trans. Veh. Technol.*, vol. PP, no. 99, pp. 1–1, 2015.

46 W. Sun, Z. Zhao, and H. Gao, “Saturated adaptive robust control for active suspension systems,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 9, pp. 3889– 3896, 2013.

47 N. Parida, S. Raha, and A. Ramani, “Rollover-preventive force synthesis at active suspensions in a vehicle performing a severe maneuver with wheels lifted off,” *IEEE Trans. Intell. Transp. Syst.*, vol. 15, no. 6, pp. 2583–2594, Dec. 2014.

48 J. Edrén, M. Jonasson, J. Jerrelind, A. S. Trigell, and L. Drugge, “Utilisation of optimisation solutions to control active suspension for decreased braking distance,” *Vehicle System Dynamics*, vol. 53, no. 2, pp. 256–273, 2015.

49 R. Wang, H. Jing, H. R. Karimi, and N. Chen, “Robust fault-tolerant H1 control of active suspension systems with finite-frequency constraint,” *Mechanical Systems and Signal Processing*, vol. 6263, pp. 341 – 355, 2015.

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